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Fiber Optic Spectral–Streak Equalizer

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DISCLAIMER

Fiber optic spectral–streak equalizer

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A spectral–streak equalizer was developed for use with an electronic streak camera to correct for material dispersion in optical fibers. Material dispersion occurs because different wavelengths of light travel at different speeds through glass fibers; the resulting difference in transit times broadens light pulses, which can lead to errors in certain scientific applications. This new instrument combines optical equalization and streak equalization techniques; it uses an array of optical fibers, as in the optical equalization technique, to partially compensate for the dispersion and uses the streak camera dynamics, as in the streak equalization technique, to complete the compensation. This paper examines the principles of equalization and compares several techniques, enumerates general and specific design considerations, outlines the calibration procedure, details efficiency estimates, describes testing techniques, gives calibration data and test results for spectral–streak equalizers currently in use, and draws conclusions from recent experience with these devices.

INTRODUCTION

During the last year, Lawrence Livermore National Laboratory (LLNL) has been developing an improved version of a high-speed gamma-ray diagnostic system. The system was designed to measure signals having bandwidths exceeding 1 GHz that are transmitted through an optical fiber over a 1-km distance.

Our system, which is similar in concept to the high-frequency-plasma diagnostic system used by Los Alamos National Laboratory (Los Alamos, NM) for the last several years,[1,2] incorporates significant changes in three areas. The detector has been made more sensitive and more radiation resistant; a single high-bandwidth multichannel recording streak camera has replaced several dozen photomultiplier tubes and oscilloscopes; and a new, versatile technique for equalizing the optical signal has been developed. This paper concentrates on this new equalization technique.

The diagnostic system consists of a Cerenkov converter optical fiber located in the gamma-ray beam, several hundred meters of high-bandwidth optical fiber (1–3 GHz/km), the spectral–streak equalizer, and a streak camera with film recording (Fig. 1).

The detection and conversion of the gamma rays to a usable optical signal relies on two somewhat inefficient physical processes. First, gamma rays are converted into high-energy electrons via the Compton process. Second, a portion of these high-energy electrons impinges on a radiation-resistant optical fiber and generates Cerenkov light. (Cerenkov light is generated whenever a charged particle traverses a transparent medium at a velocity exceeding the velocity of light in the medium. For an optical fiber having an index of refraction of about 1.5, the electron energy must exceed 174 keV to generate Cerenkov light.) Only the light falling within the numerical aperture of the optical fiber is collected.

Cerenkov light is spectrally broad, and its intensity follows a $1/\lambda^3$ dependence. Because of material dispersion in the optical fiber, a pulse that is sharp in time at the source is temporally broadened during transmission to the recording station. The extent of broadening is proportional to the length of the optical-fiber link. In the region of the spectrum that we operate (780–820 nm), the material dispersion is about 115 ps/nm·km at 800 nm. Thus, it is necessary to spectrally limit the detected signal to avoid errors caused by dispersion.

Principles of optical equalization

To preserve a system time response that meets our requirements, we must limit the effective spectral width to $\leq$2 nm. One way to do this is to use a narrow-band interference filter. This method effectively limits the spectral width, but it does so at the expense of signal strength in a system that already suffers from low signal levels arising from the inefficient Compton/Cerenkov conversion processes described above. A better way to spectrally limit the signal is to observe a larger portion of the spectrum and compensate for material dispersion by using an optical equalization technique.[3] When properly implemented, this method gives about five times the signal passed by a narrow-band filter and preserves the ≤2-nm equivalent spectral band.

The optical equalizer (Fig. 2a) uses a grating to disperse light from the transmission fiber along a linear array of optical fibers. The dispersion of the grating, the focal length of the lens, and the number of fibers are selected to preserve the desired effective spectral width. The lengths of the fibers in the array are adjusted so that all the different wavelength components of the signal generated at the source arrive at the end of the equalizer fiber bundle at the same time. That is, the longer-wavelength components (which arrive at the equalizer first) are delayed with respect to the shorter-wavelength components (which arrive later) by transmitting them through longer fibers. The output of the fiber bundle is then focused on the detector and is recorded using an oscilloscope. In this manner, the pulse, which was temporally narrow at the source and broadened during transit through the optical-fiber link, is "restored" to its original form.

Principles of streak equalization

Although optical equalization works fine when the detector is not sensitive to the fiber positions in the output array of the equalizer, such is not the case when a streak camera is used as the recording device. The output from each fiber in the array must coincide spatially at the phosphor of the streak camera since, with the streak camera, we depend on a spatial-intensity-vs-time relationship as opposed to a current-vs-time relationship in a photomultiplier tube. Hence, a fiber array output in a bundle format cannot be used with a streak camera.

To overcome this difficulty, we can use the technique of streak equalization.[4] This method again uses a grating to disperse the input signal (Fig. 2b). The dispersed spectrum now, however, is focused onto the streak-camera photocathode and generates electrons. These electrons are accelerated toward a phosphor, and sweep plates deflect the electrons across the phosphor. The electrons striking the phosphor generate light that exposes the recording film.

If no deflection voltage were applied to the sweep plates, the electrons generated at the photocathode would be focused on the output phosphor in the same pattern imaged onto the photocathode. However, by orienting the direction of dispersion in the same direction as the streak direction and applying a constantly increasing voltage to the sweep plates, the electrons generated at different locations on the photocathode can be made to strike the same point on the phosphor. That is, because the sweep voltage increases with time, electrons generated by shorter-wavelength light (which arrives last) see a stronger deflection field than electrons generated by longer-wavelength light (which arrives first). When the camera's sweep speed is carefully matched to the grating dispersion, the camera superimposes at the same point on the phosphor those signals generated simultaneously at the source.

The streak equalization technique, although effective, has some operational drawbacks. Because the grating dispersion and the sweep speed of the streak camera are intimately locked together, it is sometimes difficult to obtain the proper gratings for a given sweep speed. The only ways to tune such a system are to change the sweep speed or to change the coupling optics—both undesirable and cumbersome ways to operate. Finally, this method dictates that the streak camera and gratings be reasonably close to each other.

Principles of spectral–streak equalization

The operational difficulties of optical equalization and streak equalization can be overcome by combining the two equalization techniques. This hybrid system uses an array of fibers, as in the optical equalization technique, to partially compensate for the dispersion and lets the streak camera dynamics, as in the streak equalization technique, complete the compensation.

By using the fiber array, we decouple the interdependence of the grating dispersion and the sweep speed and also eliminate the need to have the gratings and streak camera near each other. A final advantage is that any fine adjustments to the systems can be made by trimming the lengths of the fibers in the array.

Figure 3a shows the operation of a spectral–streak equalizer system. A light pulse exits the transmission fiber and is collimated by the collimating lens; the collimated beam is dispersed by the grating into its component wavelengths, which are focused by the collecting lens onto the coherent linear fiber array of the optical equalizer. (For a system operating with a magnification of 1 ×, the width of the dispersed beam is equal to the core diameter of the transmission fiber.) Each fiber in the array transmits a segment of the spectrum. The fiber lengths are adjusted to *partially* compensate for the difference in arrival times of the various wavelengths of the signal pulse at the terminus of the transmission fiber. At the output end of the equalizer, the plane of the fiber array is oriented parallel to the streak direction. The light emerging from the array is collected by a relay lens and imaged onto the photocathode of the streak camera; the camera then completes the compensation.

DESIGN OF A SPECTRAL–STREAK EQUALIZATION SYSTEM

General considerations

In this discussion of design considerations, the equalizer portion of Fig. 3a is referred to as a dual-lens equalizer and is the type currently in use at LLNL. Several different arrangements can provide the same function, but each arrangement has advantages and disadvantages. Figure 3b shows a single-lens design generally referred to as the Littrow configuration.

The single-lens design has the advantage of using one less lens and offers some improvement in efficiency since we can place the collimating/collecting lens closer to the grating and thus collect more of the dispersed light. The main disadvantage of this design is the required proximity of the transmission fiber to the array. If the transmission fiber is attached to the fiber array, alignment of the fiber array relative to the spectral image is difficult because moving the array also moves the transmission fiber and hence the image; however, mounting the transmission fiber and fiber array separately entails problems in construction and alignment since it is difficult to provide for movement of the array (translation along the x, y, and z axes and rotation) in such a confined space.

The dual-lens design avoids these operational problems at the expense of some loss in efficiency. It is also better in rejecting stray light.

Lenses can be eliminated entirely by using a concave grating as a third alternative. However, off-axis aberrations limit the size of the fiber arrays to the point that this design does not appear very attractive.

A fourth design using a prism as the dispersing element is also a possibility. However, the spectral range of the prism would be a limiting factor since the fibers used have a peak transmission at 800 nm or more.

Design and selection of components

Lenses and gratings. Lens–grating combinations are selected on the basis of the amount of spectral dispersion that is required to cover the linear fiber array with a specific wavelength range. The linear dispersion of the spectrum in the plane of the array is expressed by[5]:

$$\frac{d\lambda}{dx} = \frac{a \cos \beta}{KF}, \qquad (1)$$

where $d\lambda/dx$ is the ratio of the required wavelength (λ) range to the linear dispersion, a is the groove spacing, β is the angle of the diffracted light measured from the normal to the grating face, K is the order number, and F is the focal length of the collecting lens.

The resolution of gratings generally exceeds the requirements for spectral–streak equalizer applications. Resolution for gratings is expressed by[5]:

$$R = \frac{a}{\lambda}(\sin\alpha + \sin\beta)N, \tag{2}$$

where R is resolution, λ is the wavelength at the midpoint in the spectral range, α is the angle between the incident collimated beam and normal to the grating face, N is the total number of grooves in the beam, and a and β are the same as above. The grating is selected to operate in the specified wavelength region required for the application.

Other factors that must be considered when selecting or specifying a lens are numerical aperture (NA), field coverage, spectral region, and resolution:

- The NA of the lenses relates to the NA of the transmission fiber and array fibers as well as the collecting efficiency of the dispersed light by the collecting lens.
- Field coverage is governed by the width of the array.
- Operating spectral region dictates the parameters for selecting materials for the elements and their coatings.
- Resolution relates to the point-spread function that affects the collecting efficiency of the fibers in the linear array.

Special-purpose three-element lenses of the Petzval configuration have been designed for our equalizers to achieve maximum efficiency. The performance characteristics of these lenses in this configuration are indicated by the modulation transfer function shown in Fig. 4.

Optical fibers. The optical-fiber bundle in the equalizer consists of fibers terminated in coherent linear arrays at each end. Factors that must be considered in designing the bundle are the number of fibers used, their type, NA, the design of the terminated ends, and the relative difference in the length of each fiber:

- The number of fibers required for maximum efficiency depends on the signal's duration and its spectral range. The equalizer's time resolution is calculated by dividing the transit-time difference between the signal's fastest and slowest components in the optical fiber by the number of fibers in the array. For example, a 2-ns transit-time difference equalized using a 20-fiber array gives a resolution of about 0.1 ns. For a signal lasting many nanoseconds, such resolution is generally sufficient, but for a signal lasting only 1–2 ns, this resolution may be inadequate. Greater resolution is obtained by increasing the number of fibers in the array, assuming that spectral coverage (and, hence, transit-time difference) do not change. Similarly, covering an expanded spectral range requires additional fibers in the array if the same time resolution is to be preserved (since a larger spectral range implies a greater transit-time difference).

- All fibers cited in the examples are high-bandpass low-loss graded-index fibers typical of those used in high-speed communication applications.

- The NA of the array fibers must be equal to or greater than the transmission fiber for a single-lens system or a dual-lens system operating at $1\times$. Maximum collecting efficiency can be achieved by making the core diameter of the array fibers larger than that of the transmission fiber, thus decreasing the amount of dead space between fibers (Fig. 5). For example, for 50-μm core fibers having a 125-μm o.d. (Fig. 5, upper array), 69% of the signal striking the array is lost because of dead space; for the 100-μm core fibers having a 140-μm o.d. (Fig. 5, lower array), dead-space loss decreases to 32%; for 200-μm core fibers having a 240-μm o.d., only 20% of the signal is lost.

- The design of the fiber array assembly on the equalizer output bundle must be given careful consideration if the streak camera is used to record several equalized channels stacked together. For example, on a recent field experiment, we recorded 11 equalized and 15 unequalized channels using one streak camera having a 30-mm-diameter photocathode. The thickness of the array assemblies thus governs the channel separation. Figure 6 shows a complete equalizer, including the output array assembly that is 1.2-mm thick and contains 20 fibers. The two holes are used to register the array assemblies.

- The relative difference in length of each fiber must be calculated. As previously stated, the material dispersion that occurs in the transmission fiber is corrected by a combination of equalizer and camera dynamics. Before calculations can be made to determine the correct length to cut the equalizer fibers, data must first be developed giving the transit times for wavelengths in the region of interest on the particular fiber that is intended for signal transmission.

One technique that has been used for developing transit time data uses a linear accelerator (LINAC) that produces pulses 40 ps wide. The short pulse of electrons generates Cerenkov light in the fiber at a known location and time. The light transits the fiber, passes through a narrow bandpass filter, and is collected by a detector system. This information allows us to calculate the transit time for that particular wavelength. The procedure is repeated using filters passing different wavelengths, thereby generating the necessary data points for plotting a curve of transit time vs wavelength. To calculate the lengths for the individual fibers in the equalizer array, transit times for a selected wavelength segment are taken from the curve, and the lengths are calculated using the following formulas:

Input data:

A = Longest transit time, in s.

B = Velocity of light in glass, in m/s (using average transit time).

C = Camera sweep speed, in mm/ns.

D = Length of the array image at the camera output, in mm.

E = Total wavelength range, in nm.

F = Total length of the transmission fiber, in m.

G = Transit time for the λ segment, in s.

H = Wavelength segment, in nm.

Calculated variables:

J = Image length of the λ segment, where $J = DH/E$.

K = Time of the sweep, where $K = 10^9 D/C$.

L = Delay in arrival time for the λ segment, where $L = A - G$.

M = Fiber delay for sweep speed, where $M = K - L$.

N = Bundle fiber length for the λ segment, in m, where $N = BM$.

Figure 7 shows a family of curves, developed using these formulas, from which a number of interesting deductions can be made. Values on the x-axis represent the maximum difference in length between the longest and shortest fibers in the bundle (at the extremes of the operating range) for various camera sweep speeds and for different signal fiber lengths.

Some important deductions that can be made from these curves are:

- As the camera sweep speed increases, more of the correction for material dispersion in the transmission fiber is done by the fibers and less by the streak camera, as indicated by the small increase in fiber length for a large change at the highest sweep speeds.

- There is a point at which the streak camera dynamics alone correct for material dispersion. This is represented by the zero difference between the longest and shortest fiber. A higher sweep speed is required to obtain this zero point with shorter transmission fibers.

- At faster sweep speeds, the longer-wavelength light must be delayed by the equalizer fibers to achieve the correct relative arrival time at the streak camera; at slower sweep speeds, the shorter-wavelength light must be delayed, as indicated by the negative fiber-length difference.

- Variations in the camera sweep speed affect the equalization process more adversely at slower sweep speeds than at faster sweep speeds, as indicated by the gradual positive slope of the curves.

CALIBRATION AND TESTING

The equalizer is aligned using a continuous source of white light. One end of a short mode-stripped optical-fiber jumper is placed in the input location of the equalizer. White light is launched into the other end of the jumper, and the end of the jumper at the equalizer is adjusted in the axial plane of the collimating lens to form a collimated beam. The dispersed image of the jumper fiber formed by the collecting lens is superimposed on the input array of the equalizer, which is then adjusted (translated along the x, y, z axes and rotated) to achieve maximum transmission. The light from the output array of the equalizer is collected, dispersed by a monochrometer, detected by a linear silicon photodiode array, and fed into an optical multichannel analyzer. The width and location of the spectrum are noted, and the grating is rotated to center the spectrum at the desired point. Figure 8 shows data derived by this technique. The individual fibers in the array are clearly resolved.

The efficiency of the equalizer system, defined as power out of the jumper fiber vs power out of the fiber bundle, was estimated using the following values for individual components:

- The transmission for the input lens at 800 nm was 95%.
- The grating efficiency was 76%.
- The second lens vignetted about 20% and had 95% transmission.
- The array had 32% dead space (for a 50-μm-wide spectrum superimposed on 100-μm core array fiber) and did not accept all the off-axis rays coming from the lens because they exceeded the acceptance angles of the fibers; 10% loss was allowed for this factor.
- The reflectance of 4% was expected at the input array fiber faces and another 4% internal reflection was allowed for at the air–glass interface of the exit end of the fiber bundle. Therefore, the total system transmission was expected to be 30% or -5.2 dB.

System transmission was measured by using a filter that limited the spectrum to a narrow region so that all the light dispersed by the grating fell on the fiber array. Measurements were taken at the transmission fiber and compared to those taken from the output array of the equalizer. The lowest system loss achieved to date with a dual-lens equalizer was -5.6 dB. The largest factors expected to increase loss are fiber misalignment and spacing between fibers in the linear arrays.

Final testing is done with the complete system assembly: a short jumper made of radiation-resistant fiber, a transmission fiber, the equalizer, fore-optics, a streak camera, and a microchannel plate. This configuration duplicates the final configuration that will be used in the field. Cerenkov light is generated in the jumper by a 40-ps LINAC pulse. If the equalizer is functioning correctly, all the light from the very short pulse is concentrated on the film record in one point about 100 μm in diameter—the limiting resolution of the streak camera/microchannel plate combination.

Figure 9a shows a 40-ps LINAC pulse recorded on a camera with a streak speed of 0.66 ns/mm. The timing marks are spaced 2 ns center to center. The difference in transit time through 628 m of transmission fiber for a wavelength difference of 40 nm centered at 800 nm was 3.04 ns; if it were not equalized, this pulse would appear as a streak of the length indicated in Fig. 9a.

A second more sensitive technique for testing the proper adjustment of the lengths of the equalizer fibers consists of rotating the output array 90° and taking a streak record of the 40-ps pulse. If the array fibers are cut to the correct lengths, the images produced by the individual fibers form a straight line. If the sweep speed is correctly adjusted for the characteristics of the equalizer, the line forms a 45° angle to the sweep direction. Figure 9b shows this phenomenon.

The 45° angle results for the following reason. When the array is oriented parallel to the sweep direction and a very short pulse is injected into the equalizer, the electrons produced by light from the longest fiber (at one end of the array) must strike the phosphor at the same point as electrons produced earlier by light from the shortest fiber (at the other end of the array). Because the array is 1.4 mm long, the distance covered by the sweep (measured at the phosphor) during the time interval between the earliest and latest light emissions must also be 1.4 mm to achieve superimposition. Hence, when the array is perpendicular to the sweep direction, the electrons are not superimposed at the phosphor, and the horizontal and vertical separations of the impact points of the earliest and latest electrons are both 1.4 mm; thus, the linear image forms a 45° angle with respect to the sweep direction.

CONCLUSIONS

We designed and constructed an efficient, operationally flexible spectral–streak equalizer system that allows streak-camera recording, gives us signal gains five times greater than bandpass filter systems, and satisfies our high-bandwidth requirements.

Our first experiment involving 11 equalized channels recorded on a single streak camera gave us excellent results, with all the equalizers meeting our design expectations.

Future requirements for greater system sensitivity are challenging us to improve the system so that it can equalize larger wavelength intervals. Our present system has adequate flexibility to satisfy these future requirements with minimal modifications.

ACKNOWLEDGMENT

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[2]J. W. Ogle, P. B. Lyons, L. D. Looney, L. Hocker, M. Nelson, P. Zagarino, T. J. Davies, R. D. Simmons, R. Selk, and B. Hopkins, Los Alamos National Laboratory, Los Alamos, NM, LA-UR-81-2136, Aug. 1981.

[3]J. W. Ogle, P. B. Lyons, and M. A. Holzman, "Signal Enhancement by Spectral Equalization of High Frequency Broadband Signals Transmitted through Optical Fibers," Proceedings of the 3rd International Fiber Optics and Communications Exposition, Information Gatekeepers, Inc., San Francisco, CA, 1980, p. 201.

[4]C. E. Stump, Jr., C. E. Gow, R. M. Malone, and J. P. Black, "A System for Broadband Material Dispersion Compensation Using the Streak Camera," Invention Disclosure, EG&G, Inc./Los Alamos Operations, Los Alamos, NM (June 1981); P. B. Lyons, Los Alamos National Laboratory, Los Alamos, NM, private communication, 1983.

[5]"Diffraction Gratings, Ruled and Holographic," Instruments SA, Inc., Metuchen, NJ, 1978, pp. 9–10.

FIG. 1. A complete high-speed gamma-ray diagnostic system consisting of a Cerenkov converter optical fiber located in the gamma-ray beam, several hundred meters of high-bandwidth optical fiber, the spectral–streak equalizer, and a streak camera with film recording.

FIG. 2. (a) Optical equalizer designed for use with a photomultiplier tube or similar device. A grating disperses the input light pulse along a linear array of optical fibers. The lengths of the fibers are adjusted so that all the different wavelength components of a signal generated at the source arrive at the end of the equalizer fiber bundle at the same time. The output of the bundle of equalizer fibers is then focused on the photomultiplier tube and recorded using an oscilloscope.

(b) Streak equalization technique. A grating disperses the input light pulse onto the streak-camera photocathode and generates electrons. These electrons are accelerated toward a phosphor, and sweep plates in the camera deflect the electrons across the phosphor. By applying a constantly increasing voltage to the sweep plates, the electrons generated at different locations on the photocathode can be directed to the same point on the phosphor. Light generated by electrons striking the phosphor exposes the recording film.

FIG. 3. (a) Configuration of the spectral–streak equalizer system currently in use at LLNL. A light pulse exiting the transmission fiber is collimated by the collimating lens and dispersed by the grating into its component wavelengths, which are focused by the collecting lens onto a linear fiber array. The equalizer partially compensates for the material dispersion that has occurred in the transmission fiber. At the output end of the equalizer, the plane of the fiber array is oriented parallel to the streak direction. The light emerging from the array is collected by a relay lens and imaged onto the photocathode of the streak camera; the camera then completes the compensation. (b) A similar spectral–streak equalizer system using a single lens to both collimate and then collect the dispersed light from the grating.

FIG. 4. Modulation transfer function curves showing the operating characteristics of the three-element 54.8-mm lenses used in the equalizer. The tests were performed at full aperture (which corresponds to *f*/1.8) with the object at infinity using a wavelength range from 630 to 670 nm. Readings were taken on axis in the sagittal and tangential orientations.

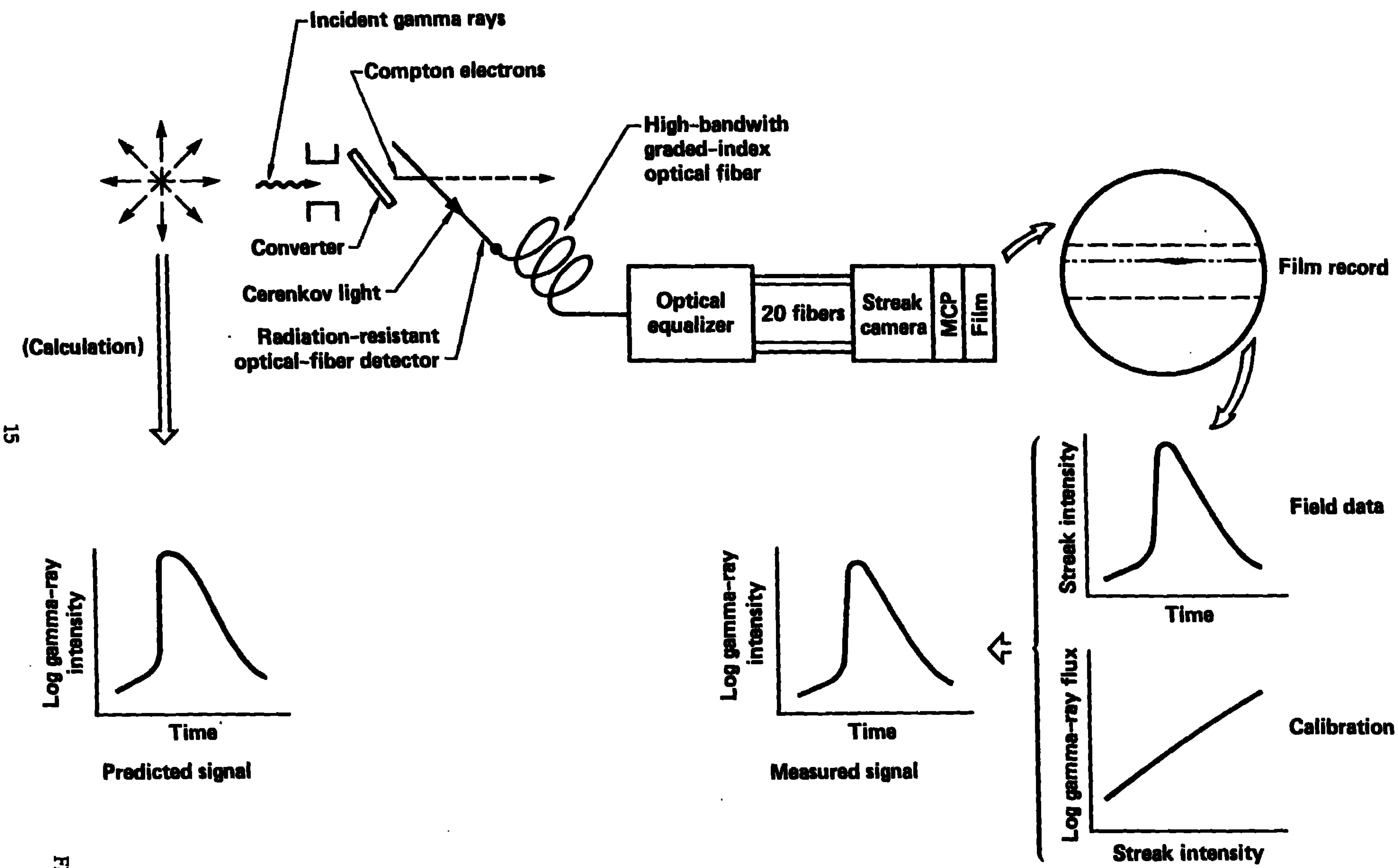
FIG. 5. Height of the dispersion grating image compared to the fiber core diameters. Increasing the array fiber-core diameter relative to the height of the dispersed image produces a considerable gain in collecting efficiency because it reduces the amount of dead space between fibers. It also reduces the sensitivity to misalignment.

FIG. 6. A complete spectral–sweep equalizer including the output array. The thickness of this array governs the channel spacing when many equalizers are recorded by one streak camera. The two small holes in the array are used to register the array assembly.

FIG. 7. Family of curves relating the difference between the longest and shortest fibers in the equalizer bundle to the camera sweep speed for several signal fiber lengths. These curves illustrate the relation of camera sweep speed to the differences in fiber lengths.

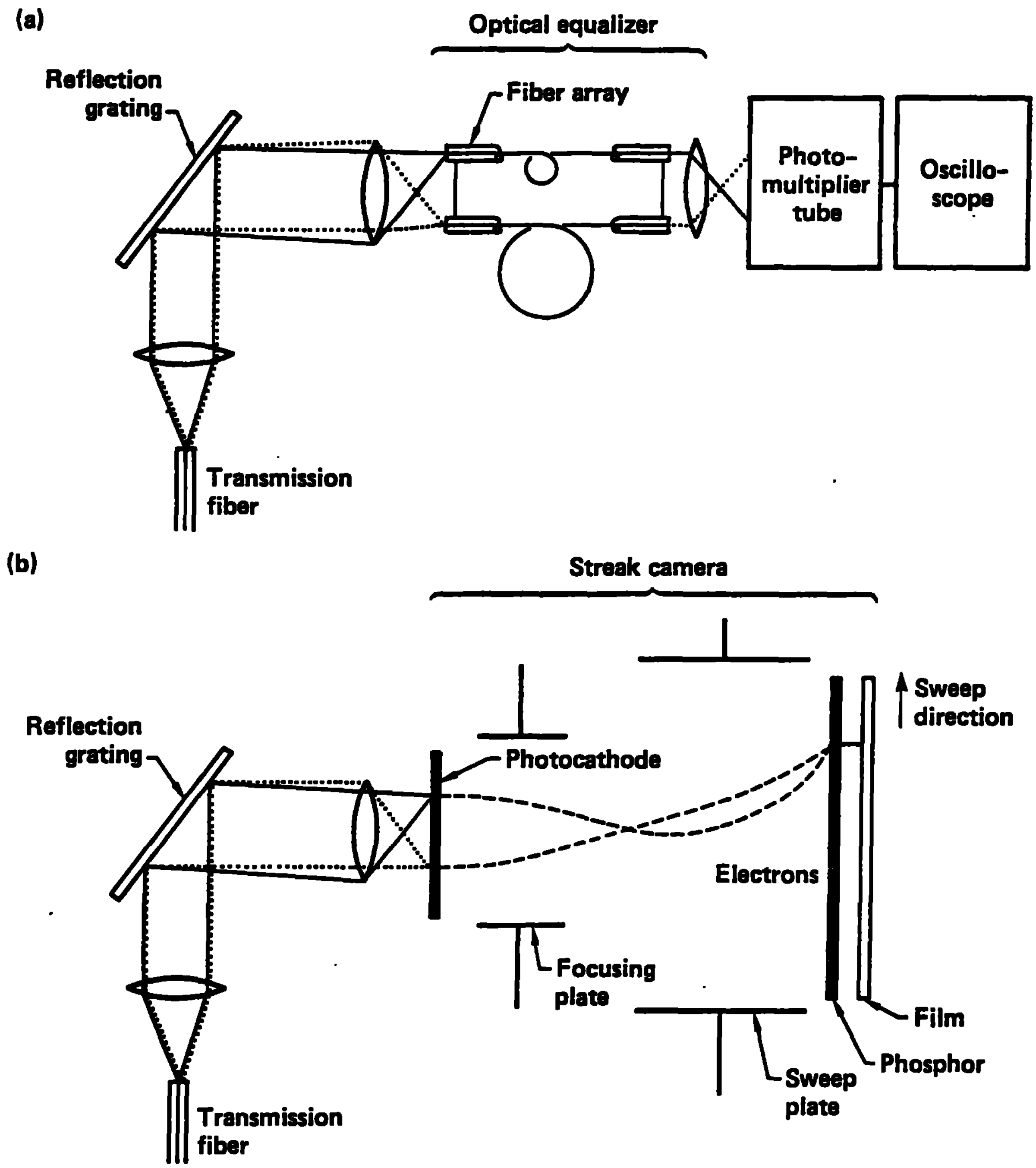
FIG. 8. Intensity vs wavelength of the spectrum transmitted through the entire system. These calibration data were obtained by directing a continuous source of white light through the entire system, detecting it using a linear silicon photodiode array, and analyzing it using an optical multichannel analyzer. The data indicate the width and centerpoint of the spectrum. In this photograph of the multichannel analyzer display, the individual fibers in the array are clearly resolved.

FIG. 9. (a) Streak camera photographic record of a 40-ps LINAC pulse that has traveled through 628 m of fiber and passed through the equalizer, fore-optics system, and camera. The timing marks along the bottom of the record are 2 ns center to center. The unequalized pulse is 3.04 ns long and would appear on the record as a streak of the indicated length if it were not equalized. (b) The same 40-ps LINAC pulse recorded after the the array was rotated 90°. If the equalizer is performing correctly, the image is oriented 45° with respect to the sweep direction.



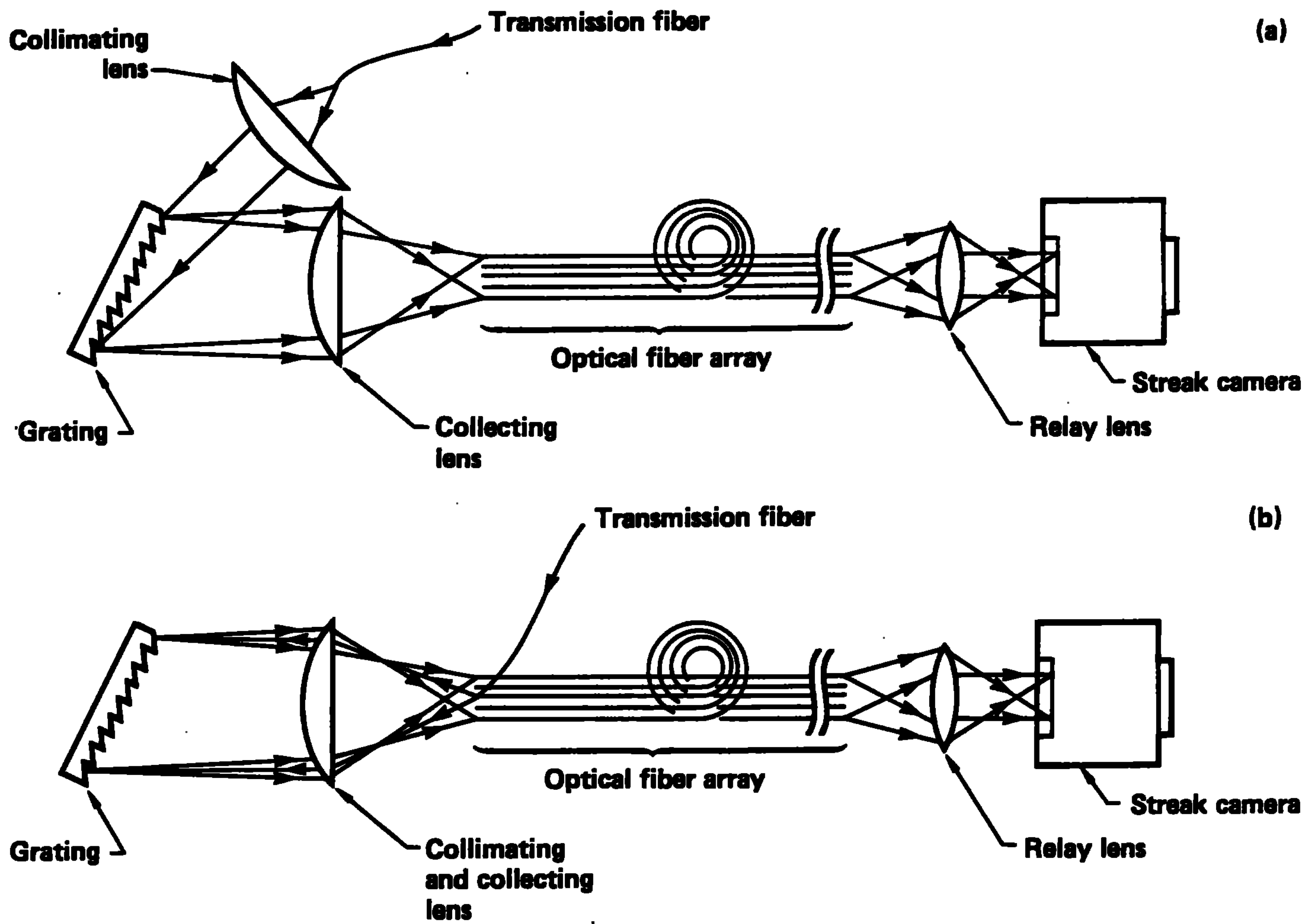
Incident gamma rays
Compton electrons
High-bandwith graded-index optical fiber
Converter
Cerenkov light
Radiation-resistant optical-fiber detector
(Calculation)
Optical equalizer
20 fibers
Streak camera
MCP
Film
Film record
Streak intensity
Time
Field data
Log gamma-ray flux
Streak intensity
Calibration
Log gamma-ray intensity
Time
Predicted signal
Log gamma-ray intensity
Time
Measured signal

FIG. 1



(a)
Optical equalizer
Reflection grating
Fiber array
Photo-multiplier tube
Oscillo-scope
Transmission fiber
(b)
Streak camera
Sweep direction
Reflection grating
Photocathode
Electrons
Focusing plate
Film
Phosphor
Sweep plate
Transmission fiber

FIG. 2



Collimating lens
Transmission fiber
(a)
Optical fiber array
Streak camera
Grating
Collecting lens
Relay lens
Transmission fiber
(b)
Optical fiber array
Streak camera
Grating
Collimating and collecting lens
Relay lens

FIG. 3

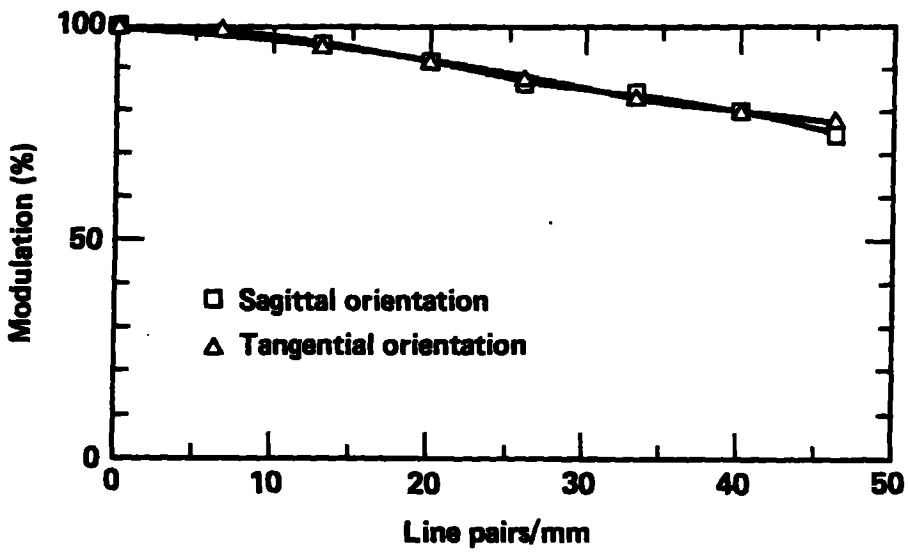

100
50
0
Modulation (%)
Sagittal orientation
Tangential orientation
0
10
20
30
40
50
Line pairs/mm

FIG. 4

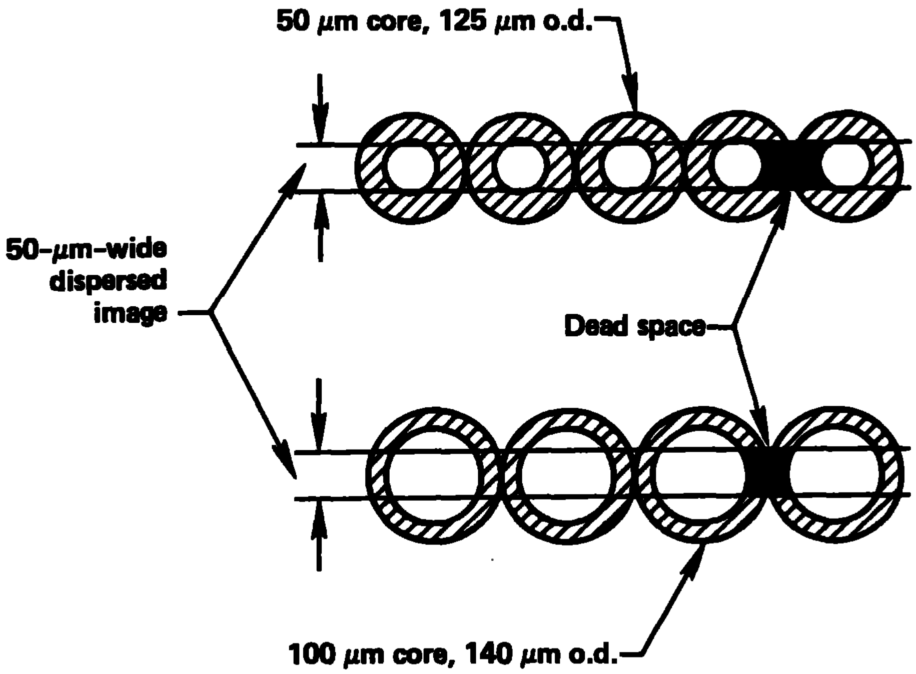

50 μm core, 125 μm o.d.
50-μm-wide dispersed image
Dead space
100 μm core, 140 μm o.d.

FIG. 5

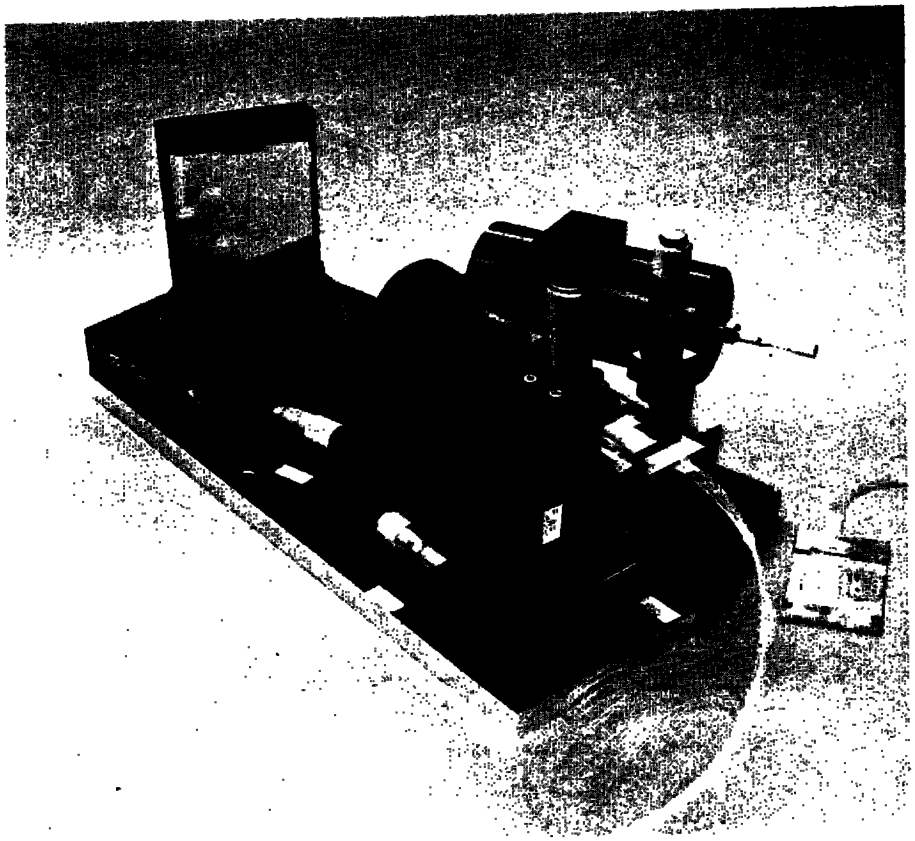
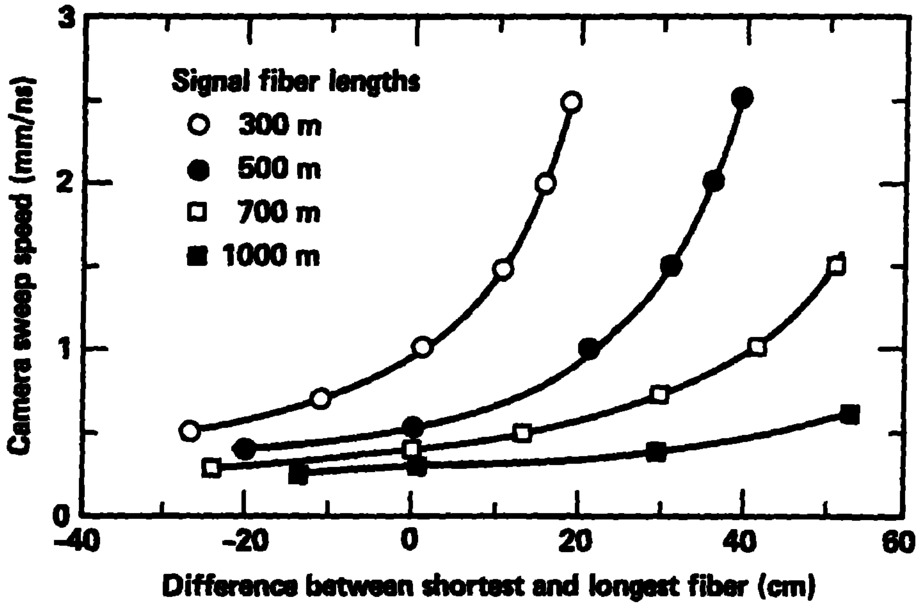


FIG. 6



Signal fiber lengths
300 m
500 m
700 m
1000 m
Camera sweep speed (mm/ns)
Difference between shortest and longest fiber (cm)

FIG. 7

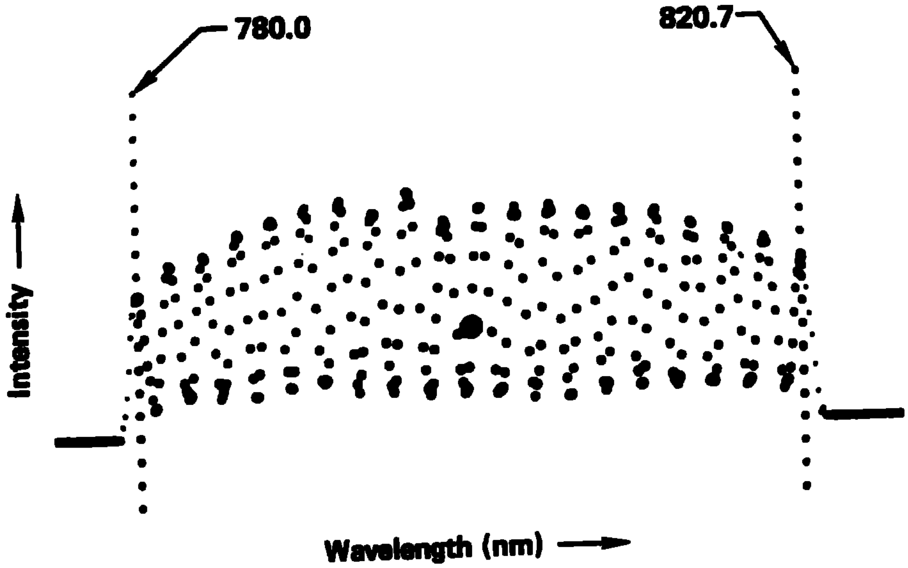


FIG. 8

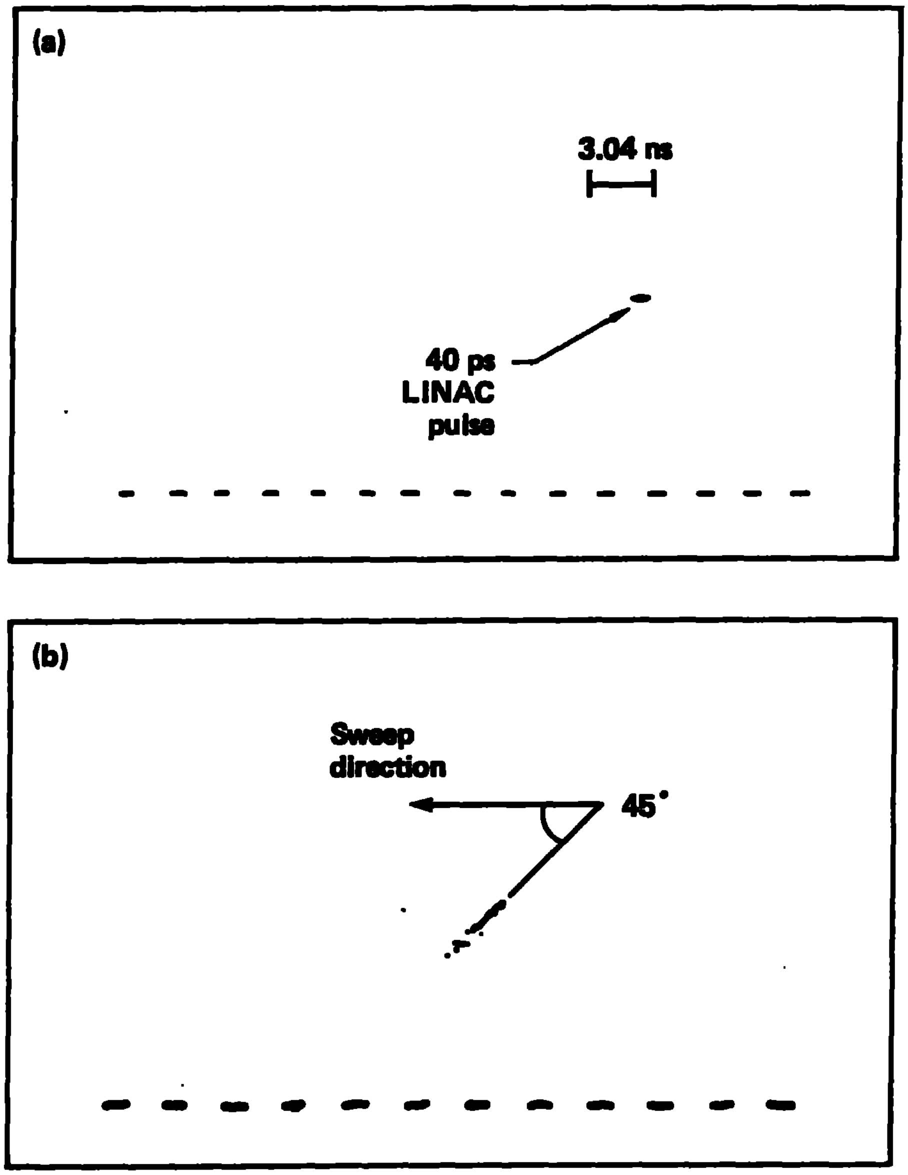


FIG. 9